Superconducting Magnet System at the 50 GeV Proton Beam Line for the J-PARC Neutrino Experiment

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***Abstract*—A neutrino oscillation experiment using the J-PARC 50 GeV 0.75 MW proton beam is planned as a successor to the K2K project currently being operated at KEK. A superconducting magnet system is required for the arc section of the primary proton beam line to be within the space available at the site. A system with 28 combined function magnets is proposed to simplify the system and optimize the cost. The required fields for the magnets are 2.6 T dipole and 19 T/m quadrupole. The magnets are also required to have a large aperture, 173.4 mm diameter, to accommodate the large beam emittance. The magnets will be protected by cold diodes and cooled by forced flow supercritical helium produced by a 4.5 K, 2~2.5 kW refrigerator. This paper reports the system overview and the design status.**

***Index Terms*—Beam line, combined function magnet, neutrino, superconducting magnet.**

I. Introduction

THE J-PARC-Kamioka neutrino experiment [1] is a next generation neutrino oscillation experiment, which will use the J-PARC [2] 50 GeV 0.75 MW proton beam to create a high intensity neutrino beam. The proton beam must be bent by 87 degrees to shoot the neutrino beam toward Super-Kamiokande located 295 km west of J-PARC. The beam line, shown in Fig.1, has an arc section whose bending radius is 105 m. A superconducting magnet system is required to bend the 50 GeV beam with the arc radius. The system was originally proposed with an optical design requiring 20 dipole and 20 quadrupole magnets. The plan was then changed to an optical design with 28 combined function magnets to optimize the cost without reducing the beam acceptance.

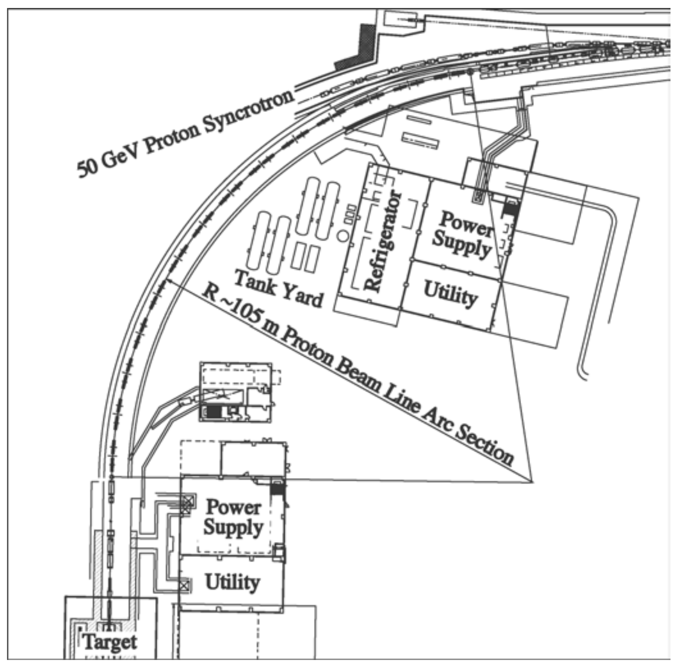

Fig. 1. Proton beam line for the Neutrino experiment at J-PARC.

Based on the new plan, a system of superconducting combined function magnets is now under development. The magnet uses two single layer left/right asymmetric coils, which simulate the sum of cos(θ) and cos(2θ) current distribution to produce a dipole field of 2.5863 T, and a quadrupole field of 18.62 T/m simultaneously. It will be the first time superconducting magnets based on such design concept is adopted for a real beam line. The magnets are designed such that they can be protected by cold diodes without protection heaters. The magnets are cooled by forced flow supercritical helium produced by a 4.5 K 2 kW refrigerator. This paper introduces the magnet design concept and summarizes the system design. The details of the magnet design [3] and the

This work was supported in part by the JSPS US-Japan collaboration program and the U.S. Dept. of Energy under Contract No. DE-AC02-98CH10886.

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study of the influence on the beam loss [4] will be presented elsewhere.

II. Magnet Design

A. Structure

The cross section of the magnet is shown in Fig. 2. The cross section is optimized for the current optics design and intended for the prototype magnet. The magnet uses a yoke collar structure similar to the BNL-RHIC magnets [5] and the LHC insertion quadrupole magnets developed by KEK (MQXA) [6]. The main parameters of the magnet are summarized in Table I.

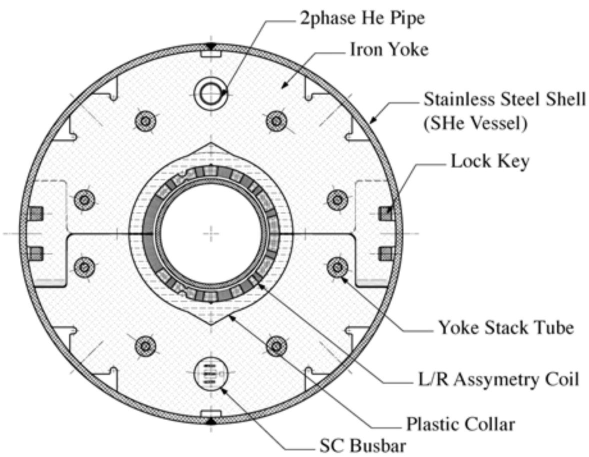

Fig. 2. Cross section of the superconducting combined function magnet.

TABLE I
Main Parameters of the Superconducting Combined Function Magnet

Parameter	Value
Beam Energy	50 GeV
Dipole Field	2.586 T
Quadrupole Field	18.62 T/m
Magnetic Length	3.3 m
Operating Current	7345 A
Operating Temperature	<5 K
Load Line Ratio	72 %
Inductance	14 mH
Stored Energy	386 kJ
Cable	LHC arc dipole outer

The coils are wound from the conductor used for the CERN-LHC arc dipole magnet outer layer coil. The conductor is already well studied and its cost is already optimized. For the conductor insulation, the system used is that of the MQXA. The coil inner diameter is 173.4 mm and the outer diameter is 204 mm. The pole of the coil is tilted towards the high field side by about 20 degrees, resulting in left/right asymmetric dipole-like coil. The coil contains 2 blocks on the high field side and 5 blocks on the low field side and 41 turns overall. The wedge shaped spacers in between the blocks are made of GFRP(G11). The coil is encased in plastic collars, which provide the ground insulation, and then held in place by the iron yoke structure. The pre-stress on the coil is 80 MPa as assembled, which is enough to compensate the maximum cool down loss of 20 MPa and the excitation loss of 30 MPa. The coil is cured with an azimuthal oversize of 0.7 mm in the low field side and 0.9 mm in the high field side to compensate the spring constant difference between the two sides. The asymmetric field also results in a difference of the pre-stress losses. The pre-stress losses are 22 MPa at the pole of the high field side and 16 MPa at the pole of the low field side.

The plastic collar is made from glass fiber filled phenol plastic, which is equivalent to that used for the RHIC magnets. The spacer works as ground insulation, which simplifies the assembly process. The spacer also sets the azimuthal alignment of the coil with respect to the yoke structure. Part of the asymmetric force at the pole is transmitted to the spacer tab. The force must be controlled within acceptable levels.

The yoke consists of two kinds of laminations, fixing laminations (5.8 mm thick) and spacer laminations (6 mm thick). They are sub-stacked in a pack about 20 cm long to simplify the yoking process. The laminations are stacked on four stacking tubes, which also provide a mechanical support between the spacer and the fixing laminations. The upper and lower yokes are locked together by steel keys and the lock is made such that the yoke mid-plane will not open. The holes at the yoke center provide the space to install the tube for the two phase helium return in the top half, and the space for the superconducting leads in the bottom half.

Construction of the magnet is completed with a 10 mm thick stainless steel shell, which also serves as the helium vessel. The magnet cold mass outer diameter is 570 mm, which is the same as the LHC arc dipole magnets, so that a common baseline design of the cryostat can be used.

B. Magnetic Design

The dipole field and the conductor peak field as a function of magnet current are shown in Fig. 3. The magnet operation current is 7345 A for 50 GeV operation and 5830 A for 40 GeV. The load line ratios are 72% and 57% respectively. The field quality of the magnet is given by the multipole expansion defined at a reference radius of 5 cm. The multipole coefficients are normalized to the dipole component with the factor 10^4. The computed multipole coefficients at 50 GeV and 40 GeV are summarized in Table II. The required quadrupole field of 18.62 T/m corresponds to the quadrupole coefficient of 3600 unit. The two dimensional cross section has been

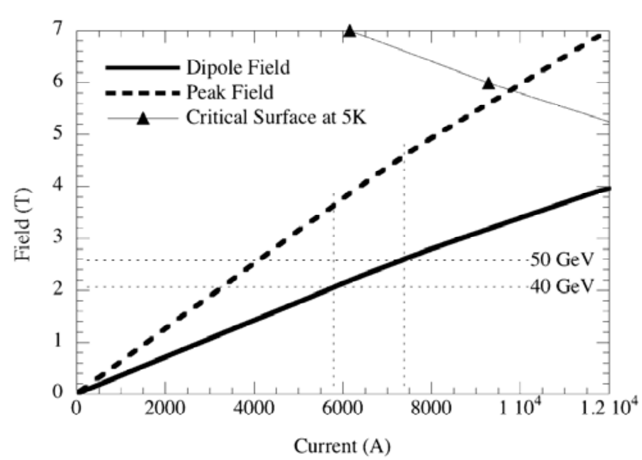

Fig. 3. Dipole and peak field as functions of current.

optimized at 50 GeV with a compensation for the end field effect.

TABLE II
FIELD QUALITY OF THE SUPERCONDUCTING COMBINED FUNCTION MAGNET @ 5 CM
DESIGN VALUE, HIGHER HARMONICS ARE OPTIMIZED FOR 40 GEV, EXCEPT FOR QUADRUPOLE WHICH IS OPTIMIZED FOR 50 GEV

	40 GeV	50 GeV
B1	2.069 T	2.587 T
b2	3642 units	3621 units
b3	0.93 units	0.84 units
b4	0.13 units	9.45 units
b5	-0.61 units	2.78 units
b6	-6.08 units	-6.32 units
b7	-0.61 units	-0.96 units
b8	-3.81 units	-3.86 units
b9	-9.01 units	-9.05 units
b10	-0.27 units	-0.27 units
b11	-3.08 units	-3.86 units
b12	2.08 units	2.09 units

C. Quench Protection

The magnets are protected by cold diodes, which are connected in parallel with each magnet. During normal operation, the cold diode is cooled by the helium, maintaining the turn-on threshold voltage at about 6 V, and preventing current from flowing through it. The growth of the normal zone during a quench gives rise to a magnet terminal voltage that eventually exceeds the turn-on voltage. Once this happens, the current flows through the diode, heating it. The forward voltage of the diode is then reduced to about 1 V due to the temperature rise. The reduction of the forward voltage enhances the current bypass to the diode and eventually protects the magnet from the over heating. The design of the cold diode assembly for the LHC arc quadrupole will be used here. The assembly consists of two diodes, each with a copper heat sink, to protect two magnets in one cryostat.

Also, a current dump circuit will be installed in the power supply system in order to protect the cold diodes and the superconducting leads. The dump resistor is set to 20 mΩ to give a current decay time constant of 20 sec. The time constant is set such that the both cold diodes and the superconducting bus-bar are protected.

A quench simulation has been performed using the magnet and the diode parameters as shown in Fig. 4. The simulation has been made based on the assumption that the quench starts at the turn experiencing the lowest field. The diode parameters are set taking into account the degradation of the diode due to radiation damage after the neutron fluence of about 2.0×10^{14} n/cm^2[8]. The simulation result shows that the maximum temperature in the magnet is about 280 K. Since the simulation was made based on the most severe condition, the magnet can be considered as self protected.

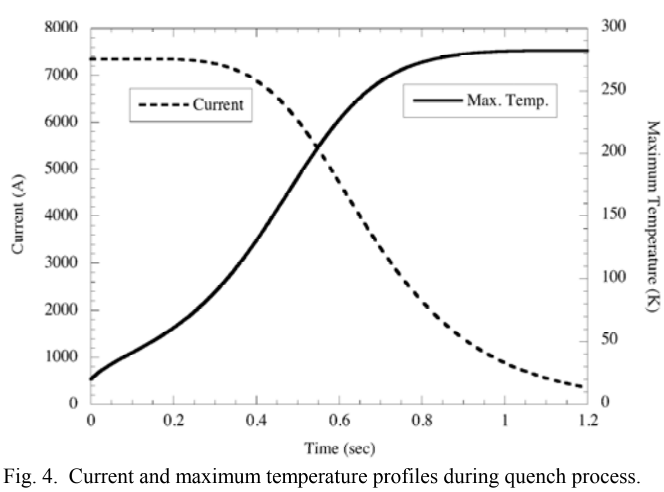

Fig. 4. Current and maximum temperature profiles during quench process.

D. Correctors

Two kinds of correctors are currently required by the optics; one changes the quadrupole component without changing the dipole, and the other is needed for vertical steering, which is skew dipole correctors. There are three options for the place to install these correctors. The first option is the surface of the cold bore tube within the magnet. This option requires space between the combined function coil and the cold bore tube, reducing the aperture available for the beam. Inductive coupling and the electromagnetic force between the correctors and the main magnet must be also considered. Another option is the end dome of the cryostat. Although the latter option avoids these problems, the strength of the corrector is limited compared to that of the bore tube correctors. The third option is conduction cooled correctors in interconnect regions. These options will be studied from magnet technology, optics, schedule, and budget points of view, until the spring of 2004 when a decision will be made. For any of these cases, the direct winding method [6] developed at BNL is considered as a prime candidate for producing the corrector coils.

III. CRYOGENIC SYSTEM

A. System Overview

The schematic flow diagram of the cryogenic system is shown in Fig. 5. The system consists of the refrigerator system, the transfer line, the cryostats, the inter-connect components, and the end boxes. The refrigerator is placed in the building at ground level. The transfer line connects the refrigerator with the rest of the system components, which will be in the underground tunnel. The transfer line contains the superconducting leads that supply 7700 A current to the magnets. The refrigerator provides supercritical helium at 0.35 MPa in pressure and 4.5 K in temperature with the cooling power of 2 kW. The supercritical helium is transferred to the upstream-most magnet by the transfer line, and then flows through the magnet helium vessels, which are connected in series. The helium is then expanded to produce 0.15 MPa, 4.5 K two phase helium that flows through the return pipe located in the yoke hole. The heat exchange between the supercritical helium and the two phase helium limits the temperature rise of the supercritical helium to the maximum temperature of 5 K. The refrigerator also supplies 80 K helium gas to cool the 80 K shield line with a cooling power of 1.5 kW. Each cryostat is equipped with a quench relief valve. This allows helium to be released to the buffer tanks when magnets quench.

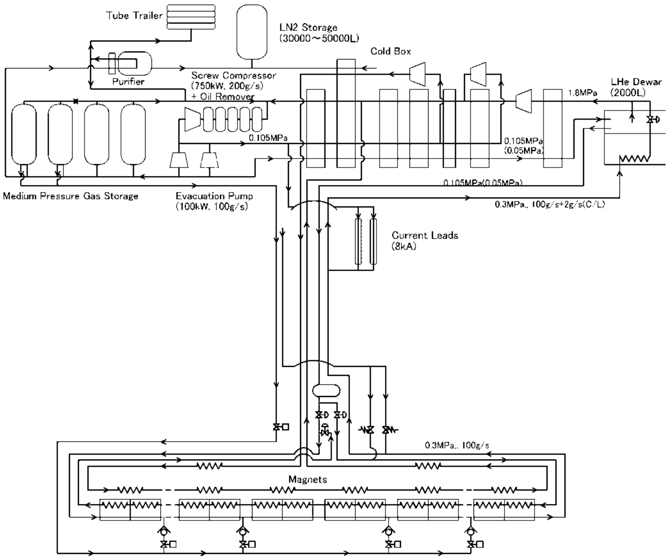

Fig. 5. Flow diagram of the cryogenic system.

B. Cryostat

The cross section view of the underground tunnel with the cryostat installed is shown in Fig. 6. The cryostat design is based on the LHC arc dipole magnets so that many of the parts are common, reducing the cost. Two magnets are encased in one cryostat. However, each magnet is supported by two support posts. The magnets are connected to each other by bellows. The magnets are mechanically decoupled and each magnet can be aligned independently within the cryostat. The heat loads of the cryostat are about 22 W to 4.5 K main helium flow and 46 W to 80 K shield for one cryostat. The total loads including that of interconnects, end boxes, transfer lines, and distribution box are about 600 W to the 4.5 K system and 1,100 W to the 80 K system.

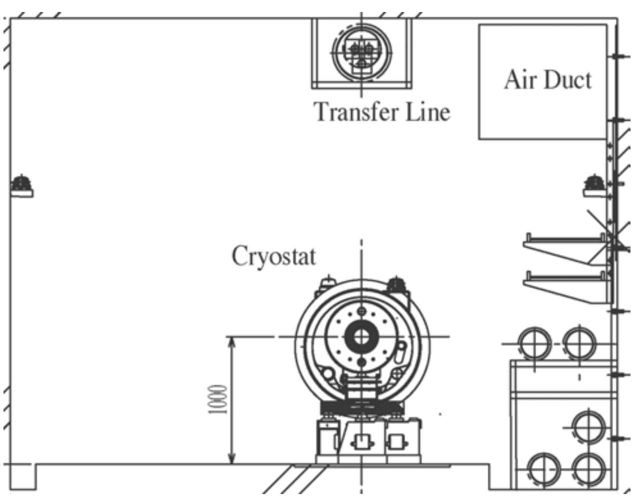

Fig. 6. Cross section of the arc tunnel of the beam line

IV. Conclusion

A superconducting beam line featuring superconducting combined function magnets is proposed for the arc section of the primary proton beam line for the J-PARC neutrino experiment. The development of the system including construction of prototypes of the combined function magnets and corrector magnets is currently under way. The R&D phase will last until the spring of 2004 when the construction of the beam line is supposed to be started.

Acknowledgment

The authors would like to acknowledge Koichiro Nishikawa at Kyoto University and Kenzo Nakamura at KEK for their strong support for the project.

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